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Formation of electron beam and volume discharge in air under atmospheric pressure

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The conditions to form electron beams in air, nitrogen, and in the mixture CO_2 - N_2 - He under atmospheric pressure have been examined experimentally. At nanosecond pulses applied to the diode, e-beam was obtained in air with amplitude of 70 A. Electron beam appears at voltage pulse leading edge having duration at FWHM not higher than 0,4 ns. After beam current ends, the discharge is usually continued in quasi-stationary mode being of a volume character.

1. Introduction

In 2002, it was demonstrated in [1, 2] how amplitude of gas diode electron beam formed under atmospheric pressure of helium [1], as well as molecular gases (air, nitrogen, or gas mixture CO_2-N_2-He) [2] can be essentially increased. Electron beam was obtained under low values of *E/p* ~ 0,1 kV/cm×Torr (*E* is electrical field strength, *p* is gas pressure) being substantially smaller than critical ones necessary for achievement of effect of "running away electrons" [3]. Earlier many scientific teams investigated formation of accelerated electrons and X-ray radiation in gas-filled diodes (see for e.g., the monograph [3] and review [4], as well as references to these papers). However e-beam amplitudes obtained in molecular gases did not exceed fractions of an ampere, and interpretation of the effect was not simple, moreover, in a number of monographs devoted to gas discharge the effect was not considered at all [5].

In this paper, study devoted to mechanism of electron beam formation at low values of *E/p* in diode filled-in with air under atmospheric pressure is presented, preliminary results were earlier published in [6].

2. Experiment

Nanosecond pulse RADAN generators described in a more detail in [7, 8] were used in experiments. Generator 1 (RADAN-303) had impedance of 45 Ohm forming with matched load voltage pulses from 50 to 170 kV at voltage pulse duration at FWHM ~5 ns and voltage pulse leading edge of ~1 ns [7]. Generator 2 had impedance of 20 Ohm forming at discharge gap a voltage pulse with amplitude of up to 220 kV and duration at FWHM as ~2 ns under voltage pulse leading edge of ~0,3 ns [8]. Gas diode construction was similar to that described in [2]. Cathode – anode distance was 13-20 mm. Electron beam extraction was made through 45-μm AlBe foil or grid. Oscilloscope TDS-864B with 1 GHz-band and 5 GS/s was used in experiments to record shunt signals. Recording method resolution was not worse than 0,3 ns.

The following facts were established on the basis of voltage pulse measurements at gas diode and beam current (see for e.g., Fig.1) as well as gap discharge form observation with varying anode-cathode gap, cathode type, and gas diode voltage value. Electron beam appears at voltage pulse leading edge having duration at FWHM not higher than 0,4 ns. Maximum of beam current is usually fixed after voltage maximum at the gap. Amplitude of beam current in optimal conditions did not exceed 30 A for generator 1 and 70 A for generator 2. With voltage increasing, beam current maximum moves to start of voltage pulse and ends at maximal voltage values at leading edge. In parallel with beam current, discharge current flows through gas diode with substantially higher value and duration than beam current amplitude and duration. The maximum of e-beam energy distribution after 45-μm AlBe foil of the first generator under air pressure in diode of 1 atm corresponded to the electron energy of ~60 keV, and in the case of the second generator it was ~70 keV, Fig.2. After beam current ends, the discharge is usually continued in quasi-stationary mode being of a volume character. Within 5 ns (generator 1) during voltage pulse at the gap the anode current density reaches ~1 kA/cm^2, specific input energy in gas is ~1 J/cm^3 and specific input power is ~200 MV/cm^3. With maximal voltage at generator 1, the value of *E/p* parameter on end of beam current is equal to ~ 0,08 kV/cm×Torr.

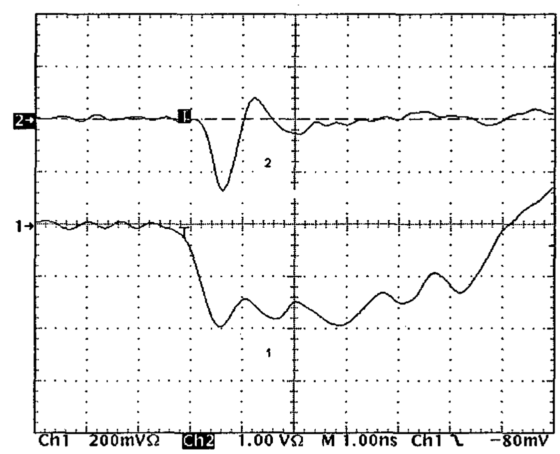

Fig.1. Oscilloscope traces of voltage pulses (1) and beam current (2). Voltage scaling is 45 kV/div, current - 20 A/div, and time - 1 ns/div. Generator 1.

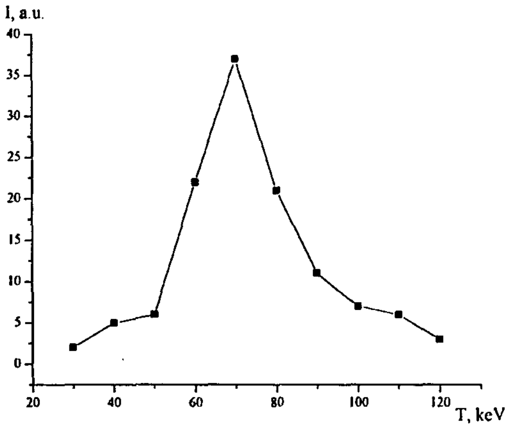

Fig.2. Distribution of electrons by energy in the beam behind the foil at air pressure in diode of 1 atm. Generator 2.

3. Discussion

Based on analysis of experimental data obtained as well as known processes occurring during gas discharge [3-5] we consider that the following dynamics of development of gas breakdown in a gap is being realized. With high-voltage pulse applied, at its leading edge the known process of electron avalanche multiplication starts with which electron concentration increases following the rule $N = N_0 exp(\alpha d)$, where α is coefficient of ionization, d is interelectrode gap. In order to obtain several kA of current during the time of ~1 ns being correspondent to the conditions of Fig.1, it is needed to have a sufficient amount of electrons near the cathode, $N_0 \sim 10^6$, which may appear due to cathode processes, during "pre-pulse" including. Along with development of discharge, the number of electrons in every avalanche could increase in $\sim 10^8$ times and above [5] without formation of streamer, and then within voltage pulse leading edge the electron amount reaches 10^{14} and more that with $E/p \sim 0{,}05\text{-}0{,}1$ kV/cm×Torr sufficient for discharge current of more than 1 kA. Electron beam is registered after ~0,5 ns following application of voltage pulse either with grid anode or foil one. Its formation, as we earlier supposed in [2], is connected with achievement of critical field in the space between plasma front from broadening to anode avalanches and anode. Note, that on avalanches growth plasma front consists of electrons, correspondingly, the space charge of electron cloud gives additional acceleration to anode for the electrons located at the edge of electron cloud. A part of electrons can have higher energy here than voltage at the diode is. It is clear that the number of electrons in a beam must be essentially smaller than number of electrons in avalanches, and the number of electrons with energy exceeding applied voltage value must be essentially lower than the number of them with average energy. After beam electrons reach anode, the field in the gap becomes rather improved, and electrical field gradient sufficient for "running away electrons" disappears.

Maintenance of volume character of discharge in gap within the whole voltage pulse, Fig.1, is determined by avalanche discharge character in the first stage and pre-ionization by electron beam formed during discharge. Stabilization of discharge current amplitude at high fields in the gap ($E/p \sim 0{,}05\text{-}0{,}08$ kV/cm×Torr) may be determined by increased energy losses of secondary electrons while they pass through plasma formed within discharge development as well as due to process of recombination. We consider this discharge type to be different from those described in [3-5] being in future widely applied in various fields (formation of subnanosecond electron beams, pumping of pulsed lasers on dense gases, etc.).

4. Conclusion

An electron beam has been obtained in atmospheric air with amplitude of 70 A with electron energy of 70 keV. Electron beam appears at voltage pulse leading edge having duration at FWHM not higher than 0,4 ns. The major part of running away electrons with rather low initial values of E/p ~ 0,05-0,1 kV/cm×Torr form in cathode plasma - anode gap. Cathode plasma propagates to anode at a high velocity, at that with electrical field distribution in gas diode area the critical value of E/p is being reached, either due to geometric quotient, leading to formation of subnanosecond electron beam. After beam current ends, the discharge is usually continued in quasi-stationary mode being of a volume character. The density of current reaches ~1 kA/cm^2, specific input energy in gas is ~1 J/cm^3 and specific input power is ~200 MV/cm^3.

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